

Chapter 3

Modeling Approach to Study the Riverine Flood Hazard of Lower Damodar River



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Abstract Flood is the hydraulic response of the river to the rainfall excess runoff generated in the natural watershed due to high rainfall events. The accuracy of flood damage evaluations depends on the understanding of the occurrence of flood events and the areas that are vulnerable to flood damage. Hydraulic and hydrologic models have gained significant importance among hydrologists for flood study. The objective of this study is to identify the locations along the lower Damodar river which are susceptible to flood. One dimensional hydrodynamic model using MIKE HYDRO RIVER was prepared for flood of 20 year return period in the lower Damodar river. For the Manning's n value of 0.03, the model output data (water depth) match closed to observed water depth at three gauge station. Furthermore, NSE, PBIAS, and RSR were used for determining the model performance. A good agreement was detected between the model output and the observed data at the gauging stations. The finding of the study indicated that majority of river discharge (65% to 70%) is carried by Mundeswari river and 30% to 35% carried by Amta Damodar in lower part of the Damaodar river. Encroachment in the riverine system for agricultural purposes,

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changes in the LULC due to recent developments, and activation of local minor distributaries during the peak monsoon season with inadequate capacity in these low-lying areas aid the spatial extent of the flooding.

Keywords Flood · Hydrodynamic Model · MIKE HYDRO RIVER · Remote Sensing

3.1 Introduction

Disasters are as ancient as human civilization. Disasters are events of severe disruption that causes monetary, material, human, and environmental losses, and they also adversely affect the progress of a country. Disasters can be natural or man-made. Natural disasters include floods, cyclones, cloudbursts, snow avalanches, earthquakes, hailstorms, and landslides, whereas man-made disasters refer to railroad accidents, fires, and leakages of chemicals/ nuclear installations, among others. The phases of all disasters are the same, whether such disasters are natural or man-made. India as a nation is highly vulnerable to cyclones, floods, droughts, and earthquakes. Every year, food security, health infrastructure, agriculture, economy, and environment are adversely affected by natural disasters. The nation's infrastructure encounters a wide range of direct and indirect losses due to various disasters. The productivity of crops and agricultural land suffers huge losses due to droughts. Floods and cyclones cause immense damage to infrastructure, whereas damage to agriculture depends on the relative agricultural cycle. India as a nation is highly vulnerable to cyclones, floods, droughts, and earthquakes. Every year, food security, health infrastructure, agriculture, economy, and environment are adversely affected by natural disasters. The nation's infrastructure encounters a wide range of direct and indirect losses due to various disasters. The productivity of crops and agricultural land suffers huge losses due to droughts. Floods and cyclones cause immense damage to infrastructure, whereas damage to agriculture depends on the relative agricultural cycle.

Flood is the hydraulic response of the river to the rainfall excess runoff generated in the natural watershed due to high rainfall events. It is extensively destructive natural disasters causing massive societal and monetary loss to several nations globally (Mosavi et al. 2018). In present time floods become a huge problem due to fast land use change, channel blockages in low-lying areas, sedimentation in river, urban sprawl in areas prone to flooding and population growth (Pramanik et al. 2010; Singh et al. 2020). The distinctive circumstances of information are vital to learning about flood occurrence (e.g., hydrological aspect means the intensity and frequency of rain, hydraulics aspect refers to the response of river to rainfall, geographical aspect pertains to flood zone, environmental aspect is the damage to the system, and civil engineering aspect denotes the response of a structure to the flood hazard). The accuracy of flood damage evaluations depends on the understanding of the occurrence of flood events and the areas that are vulnerable to flood damage. Thus,

gaining an understanding of the catchment area response to river discharge during rainfall is critically important.

The primary aim of flood risk analysis is to evaluate the probable consequences related to the incidence of flooding in an area. During earlier periods, flood risk was primarily related to the prospect of hazard incidence. However, flood risk nowadays is also associated with the susceptibility of the system to damage. To develop a flood control system, obtaining knowledge regarding the occurrence of flood and its after effects is crucial. Although flood cannot be wholly evaded, its hazardous effects can be weakened usually by structural or non-structural approaches. On the one hand, structural modes involve designing and building a river embankment or a reservoir structure to safeguard the flood vulnerable areas. On the other hand, non-structural methods entail defining the flood zoning area and developing an early flood warning system that can help with shifting the affected individuals during a flooding. Non-structural approaches nowadays have become more popular than flood protection works because earlier is a cost-effective system.

Hydraulic and hydrologic models have gained significant importance among hydrologists for river basin management in situations involving the investigation of real-time prediction (Bates and De Roo 2000; Hsu et al. 2003; Pappenberger et al. 2005; Jung and Merwade 2011; Pappenberger et al. 2006; Quiroga et al. 2016; Noh et al. 2019; Nyaupane et al. 2018). Abdella and Mekuanent (2021) applied hydrodynamic models on Kulfo river in southern Ethiopia for riverine flood mitigation. The simulation of real flood events using factual hydrological data along with geometric data for specific river system is performed in the flood model. Based on the simulation of the flood model, the characteristics of flood risk can be determined at a particular instant of time. With the advancement of technology, computational time has significantly reduced during flood mapping. In hydrological modeling, remote sensing (RS) data are frequently used for the preparation of geometric data and a thematic map in the absence of field data. Geospatial technologies provide powerful capabilities for natural hazard planning, monitoring, and mitigation. Geographic Information System (GIS) is used for identifying vulnerable areas; moreover, the representation of existing terrain is possible through spatial tools and modeling techniques (Saraf and Choudhury 1998; Chowdhury et al. 2010; Meyer et al. 2009). The use of computer-based systems in support of decision making in different phases of disaster management has dramatically increased over the past decade. With advances in computer technology, this computational limitation is being resolved (Morales-Hernández et al. 2020). Enhanced computing power has enabled large-scale flood modeling applications ranging from regional to national scales (Ashrafi et al. 2017; Yu et al. 2017; Wing et al. 2019). Spatial decision support system (SDSS) has gained importance among decision makers that incorporates the computational capabilities of computers to understand the response of complex physical systems during a disaster (Shankar and Mohan 2005; Sinha et al. 2008; Boroushaki and Malczewski 2010).

3.2 Rational of the Study

Floods and cyclones cause immense damage to infrastructure, whereas damage to agriculture depends on the relative agricultural cycle. The EM-DAT is a global database formed by the funding of the WHO and the Belgian government. According to Emergency Events Database (EM-DAT), in the past four decades on a worldwide level, floods caused maximum economic damage among natural disasters, except for a few years in which earthquakes predominated, as shown in Fig. 3.1. Keeping in view aforementioned issue present work prepared a 1-D hydrodynamic model for lower Damodar river using high resolution RS data. The purpose of this study is to identify the locations along the lower Damodar river which are susceptible to flood. Present study used MIKE HYDRO RIVER software developed by DHI to prepare 1-D model. Thus, the aim of this study is to boost the understanding of the flooding problem of the lower Damodar river by preparing a hydrodynamic model. Study area map is shown in Fig. 3.2.

3.3 Limitations of the Study

In this study 1-D hydrodynamic model was considered for riverine flood of the Damodar river in which geometric data of river cross-section was extracted from high resolution remote sensing data. 1-D model is better for river flow but for floodplain areas analysis its results will be conservative.

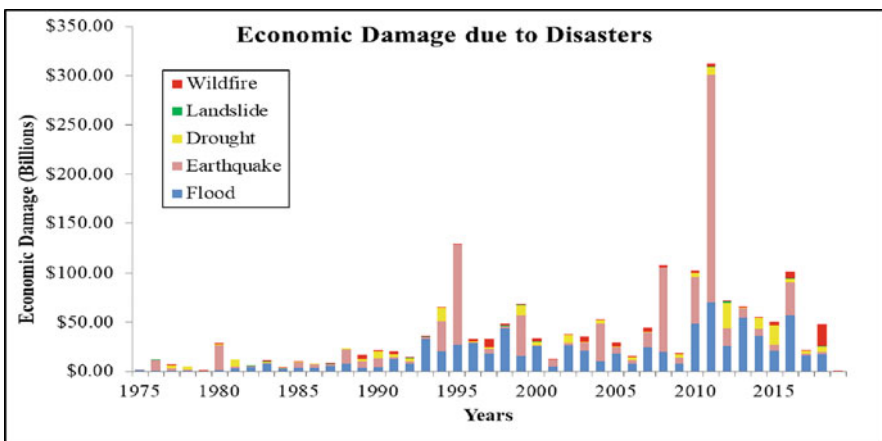


Fig. 3.1 Representation of economic damage by the different types of natural disaster (Source: EM-DAT 2018)

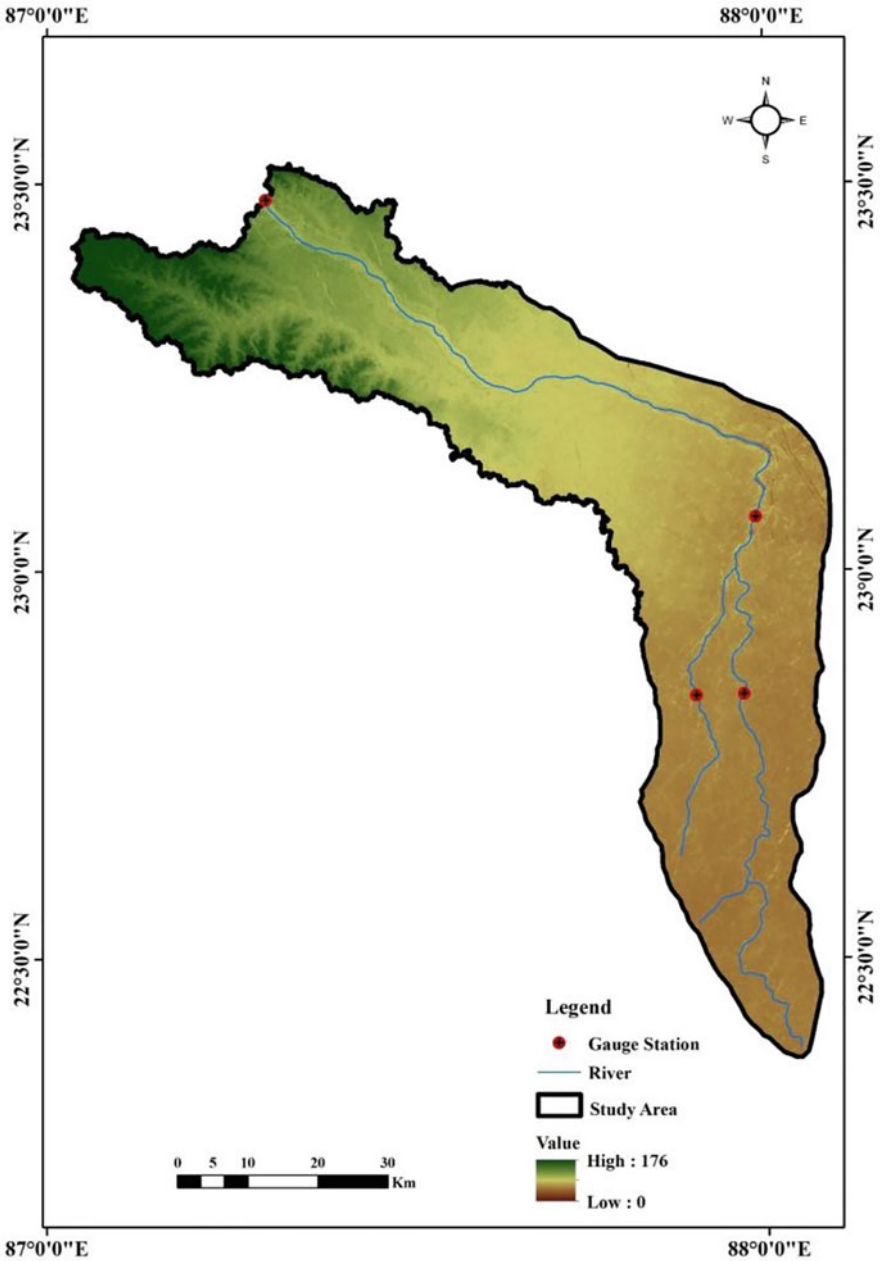


Fig. 3.2 Location map of the study area

3.4 Materials and Methods

The methodology of the study field consists of three phases, namely data collection, data processing, and preparation of the hydrodynamic model. River discharge data were collected from concerned government office. High resolution RS data were acquired from the National Remote Sensing Centre Hyderabad for the input data preparation of the model. In the field visit, data such as base flow depth, LULC, river depth, cross-section width, and settlement location near the river were collected to validate the model setup. At 15 cross-sections location width of the river and water depth were measured in field. Total station, handheld GPS, distometer, measuring tape, and other accessories were used during a field survey. Flowchart of the applied methodology is shown in Fig. 3.3.

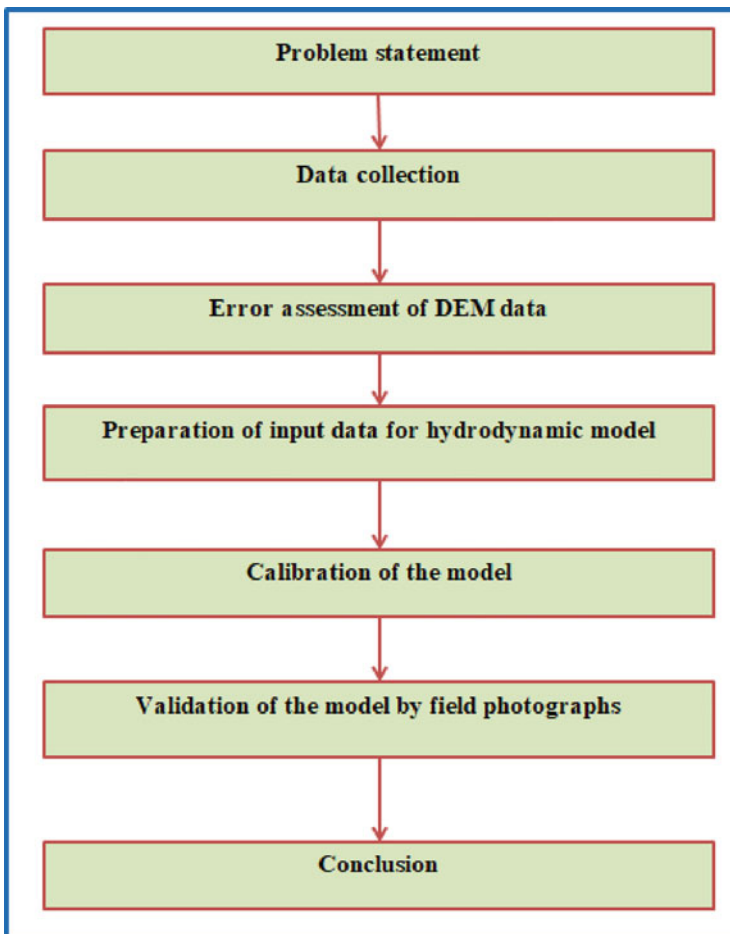


Fig. 3.3 Flowchart of the applied methodology

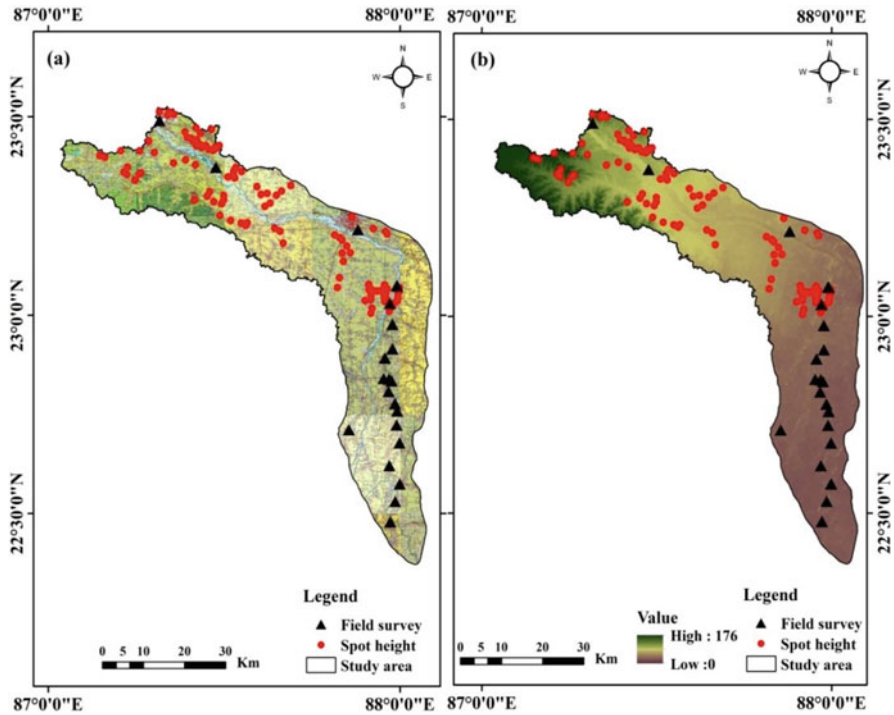


Fig. 3.4 (a) Location of spot height point in toposheet. (b) Location of elevation point in DEM

River network shapefiles and river cross-section files were prepared in ArcGIS 10.5 using high resolution Cartosat-I (spatial resolution of 2.5 m) satellite imagery and imported in the MIKE HYDRO RIVER model. Cartosat DEM was used for extracting the river geometry. Modification of DEM was conducted by subtracting the RMSE (Eq. 3.1) value from the original DEM elevation value to bring the extracted geometrics as close as possible to the ground value. Location point of spot height in toposheet and DEM elevation point is shown in Fig. 3.4a, b. Comparison of both data is shown in Fig. 3.5.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (Z_s - Z_{DEM})^2} \tag{3.1}$$

where

Z_s = spot height from toposheet.

Z_{DEM} = elevation height from DEM.

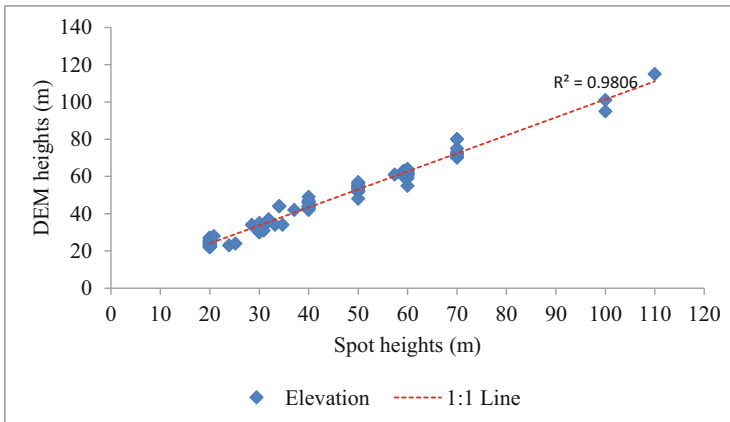


Fig. 3.5 Comparison between spot height and DEM elevation

3.5 Results and Discussion

One-dimensional hydrodynamic modeling was carried out to identify weak levee point along the lower Damodar river which is susceptible to flooding. A 1-D model is best for representing the flows inside the interconnected systems of channels. MIKE HYDRO RIVER is extensively used for the 1-D modeling of rivers, streams, and channels. The St. Venant Equation is the core of a 1-D hydrodynamic model. Peak flood event of 20 years return period was selected for simulation of the model. All the input geometry files were generated in GIS-compatible format using high resolution RS data. For Upstream boundary condition of the model daily discharge data and for downstream Q/h curve was utilized. Model was run from the July 1 to October 15, 2009 period. For model calibration Manning's roughness coefficient (n) was used as a calibrating parameter.

In modeling studies, calibration is required for identifying key factors by matching the model output data with the observed data for a given set of assumed conditions. The key target of calibration is to increase the accuracy of the model. Multiple statistics index that covers all the aspects of the hydrograph is used for assessing the performance of the model (Boyle et al. 2000). In the present study, Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), and RMSE–observations standard deviation ratio (RSR) were used for determining model performance. The value of NSE varies between $-\infty$ and 1.0, and the best value is represented by $NSE = 1$. PBIAS evaluates the normal inclination of the predicted data of the model to be greater or lesser than their corresponding observed data (Gupta et al. 1998). RSR integrates the assistance of error index statistics. Equations of statistics index are presented below from Eqs. 3.2–3.4.

Nash–Sutcliffe efficiency (NSE)

$$\text{NSE} = 1 - \frac{\sum_{i=1}^n (Y_{i_{\text{obs}}} - Y_{i_{\text{sim}}})^2}{\sum_{i=1}^n (Y_{i_{\text{obs}}} - Y_{\text{mean}})^2} \quad (3.2)$$

Percent Bias (PBIAS)

$$\text{PBIAS} = \frac{\sum_{i=1}^n (Y_{i_{\text{obs}}} - Y_{i_{\text{sim}}}) \times 100}{\sum_{i=1}^n (Y_{i_{\text{obs}}})} \quad (3.3)$$

RMSE–observations standard deviation ratio (RSR)

$$\text{RSR} = \frac{\text{RMSE}}{\text{Standard deviation}} = \frac{\left[\sqrt{\sum_{i=1}^n (Y_{i_{\text{obs}}} - Y_{i_{\text{sim}}})^2} \right]}{\left[\sqrt{\sum_{i=1}^n (Y_{i_{\text{obs}}} - Y_{\text{mean}})^2} \right]} \quad (3.4)$$

$Y_{i_{\text{obs}}}$ = i th observed field data, $Y_{i_{\text{sim}}}$ = i th model simulated data, Y_{mean} = observed mean data, n = total number of observations.

Selection of initial roughness coefficient (n) in the model for the channel is based on the guidelines mentioned in the available literature (i.e., Chow 1959) and in model it varied from 0.02 to 0.045 during calibration process. Simulated water depth from the model compared with the observed water depth which shows both the data were close for roughness's (n) value of 0.03 at gauging station. Observed data and the simulated data of water depth was plotted around 1:1 line to estimate the deviation in both values. In this study, the residual plots for all three gauge stations for 2009 were plotted. The residual is the difference between individual observed and model values. The residual plot suggests an opportunity to improve the model. For the years 2009 all the graphs were plotted simultaneously for each gauge station as shown in Figs. 3.6, 3.7, 3.8, 3.9, 3.10. Performance of the model based on three statistics is given in Table 3.1.

Water level difference error occurred as the model used DEM-extracted river cross-sections. As simulation period proceed variation of input discharge reflected in the water depth curve at selected gauge stations, but the curve not self-attuned as quickly as the observed water depth curve due to the frequency of flow data. From the residual plot, water depth predicted by the model was observed to be on the higher side. In the residual plot, some data points showed a higher residual value due to the lag of time, as the frequency of flow was moderate, which could be minimized by increasing the frequency of flow data. The absence of a sufficient amount of observed data due to the lack of gauge stations in certain important locations reduced the accuracy of the model. The frequency of the observed data has a vital role in enhancing the accuracy of the model which means whether the data are available on an hourly, daily, or monthly basis.

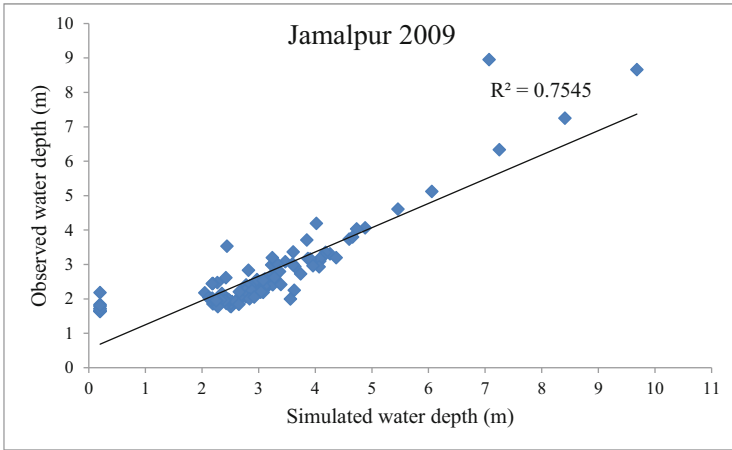


Fig. 3.6 Observed and Simulated water depth around 1:1 line at Jamalpur in 2009

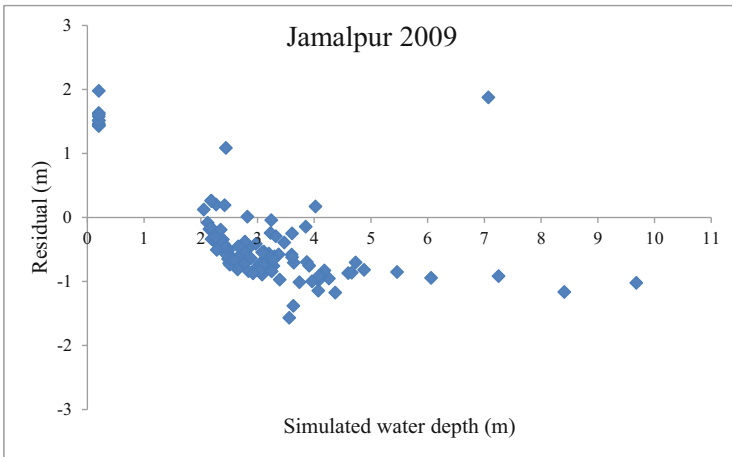


Fig. 3.7 Residual plot of water depth at Jamalpur in 2009

3.5.1 Validation

The validation of the model comprises a simulation of the model using input parameters estimated by the calibration process. For the validation of the model in this study, information collected by local people’s experiences about the flood-affected areas during past flood events, field visit photographs at key sites were utilized. The questions posed to the local people in flood-affected areas during the field survey are as follows: When did you arrive at these area? What was the extent of the increase in water level during flood times?

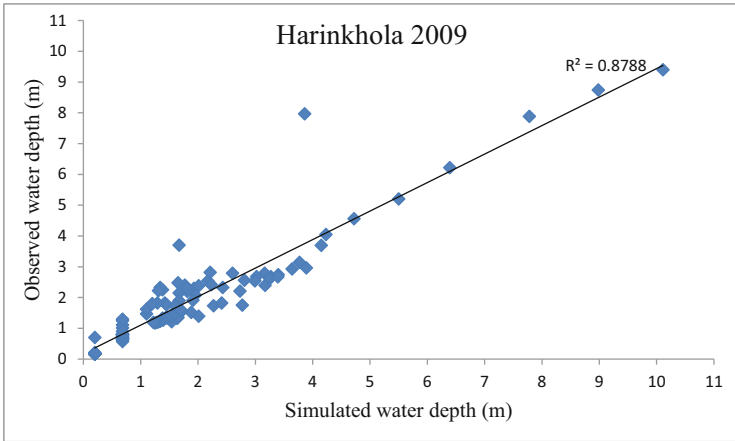


Fig. 3.8 Observed and Simulated water depth around 1:1 line at Harinkhola in 2009

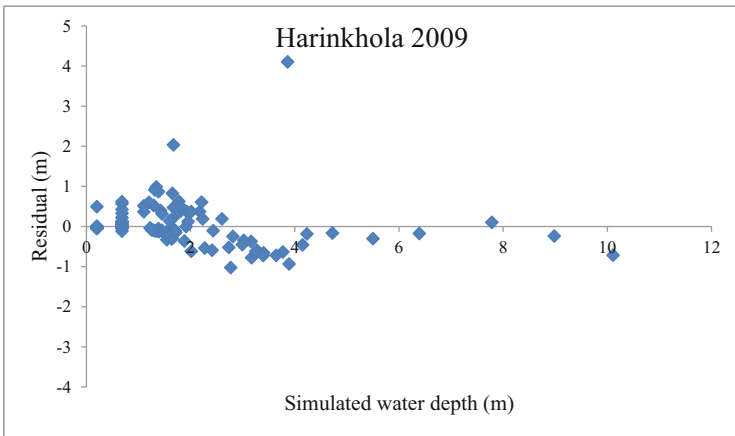


Fig. 3.9 Residual plot of water depth at Harinkhola in 2009

Figures 3.11 and 3.12 shows the field validation of model predicted water depth at Amarpur, and Joynagar along with chainage. In the validation map, the blue line shows the water level, the red line represents the left levee bank, and the green line shows the right levee bank. We obtained the information on the extent of water raise point at flood times by interacting with the local people in flood-affected areas. This information was implemented during the validation of the model and verification of whether that point was attained by the model output or not. At Amarpur location, the cross-section was extended to the nearest high elevation point, which was a road and flood water level in the field indicated by blue line (Fig. 3.13). At Joynagar (Fig. 3.11) flood water touched up to nearest road and building as shown by blue line. Field validation photographs were shown with the model output. We

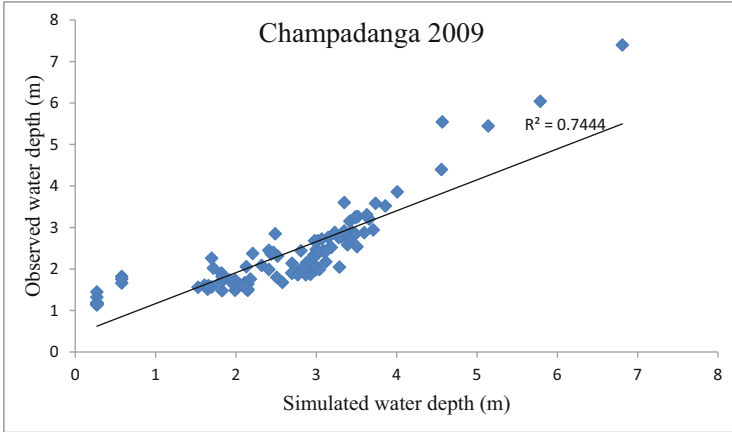


Fig. 3.10 Observed and Simulated water depth around 1:1 line at Champadanga in 2009

Table 3.1 Performance of the model

Statistical performance measures	Jamalpur	Harinkhola	Champadanga
NSE	0.81	0.90	0.66
PBIAS	-13.17	1.76	-9.86
RSR	0.43	0.31	0.58

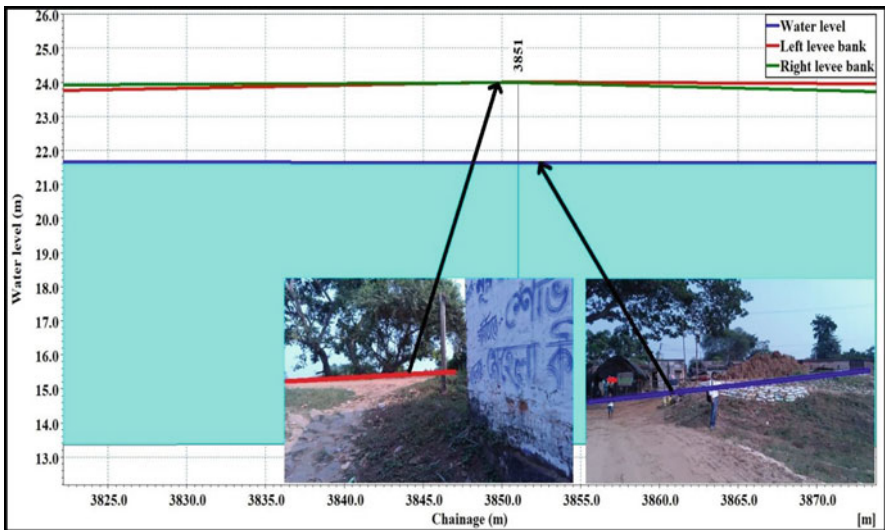


Fig. 3.11 Map showing field validation with model output at Amarapur

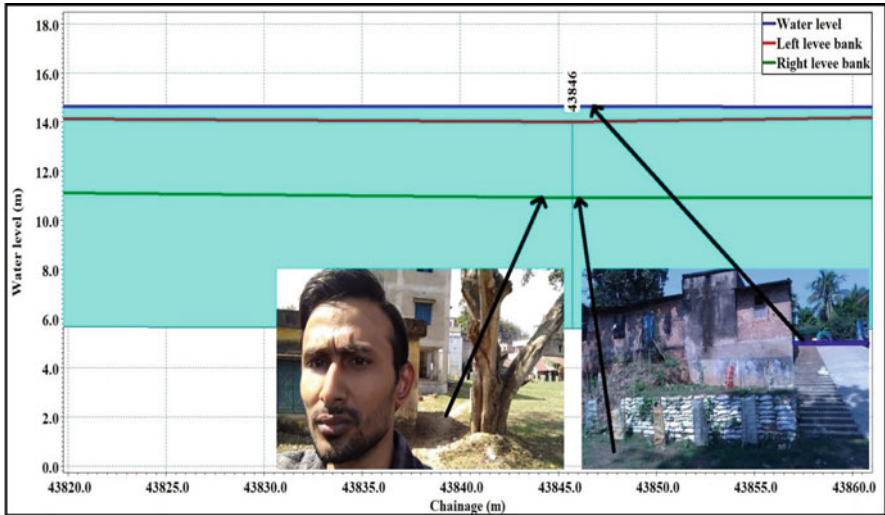


Fig. 3.12 Map showing field validation with model output at Joynagar

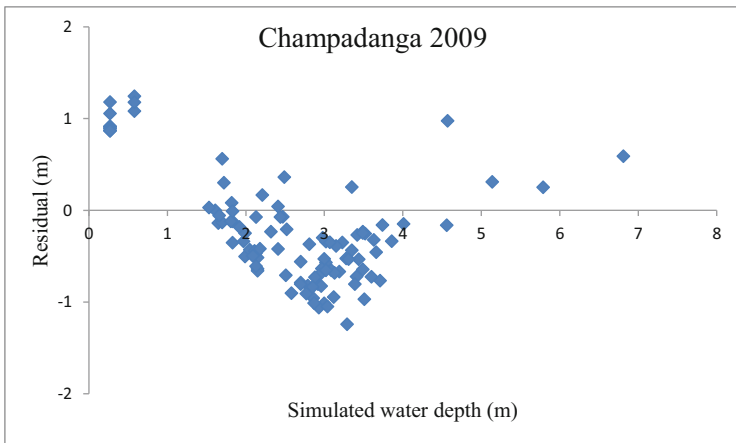


Fig. 3.13 Residual plot of water depth at Champadanga in 2009

endeavored to validate the model as accurately as possible; however, we could not obtain the accuracy up to that level due to some limitations in the same manner that we acquired the accuracy in current flood events and actually measured the experimentation works. From model simulated water depth profile (Fig. 3.14) it was found that due to narrower river cross-section and reduced carrying capacity of the river overtopping of water mostly takes place in downstream section of the river.

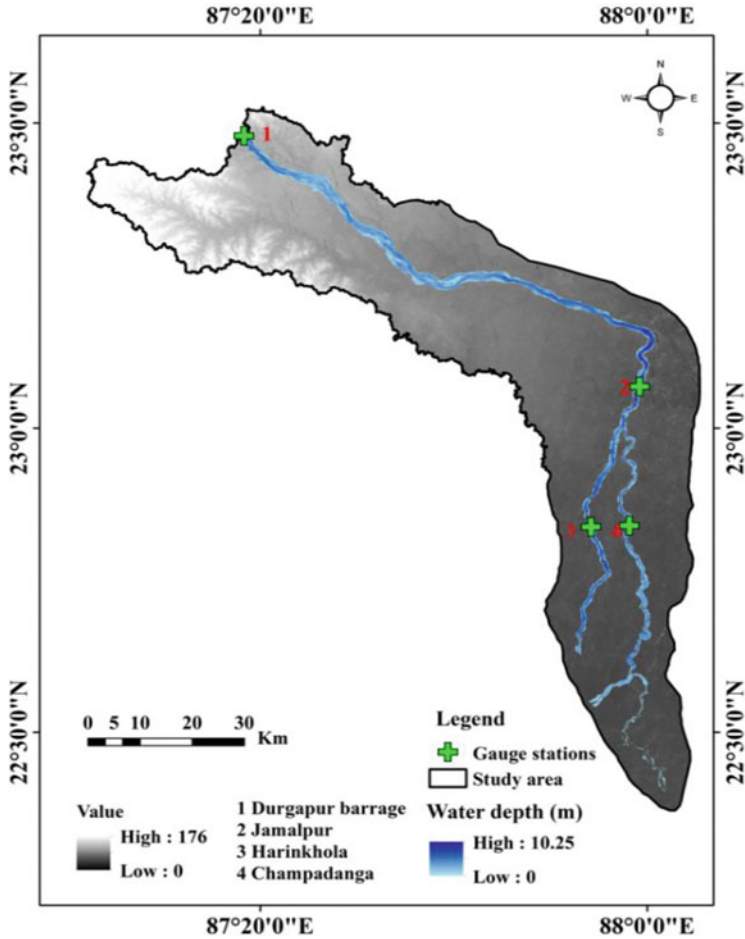


Fig. 3.14 Predicted Water depth map by the model overlaid on DEM

3.6 Recommendations

To minimize flood problems in the lower Damodar basin, desilting should be carried out in the main river and distributary channels that are active during floods. Land encroachments and illegal constructions in the flood plains of the Damodar River should be removed to minimize flood damage. As predicted by the model, embankments of less strength should be repaired and earthen banks parallel to the river’s path at flood vulnerable points should be reconstructed. Also, the height of existing embankments at critical locations should be raised. Confining the river’s path frees large areas from floods and consequently reduces damage intensity.

3.7 Conclusions

Present study used one dimensional hydrodynamic model (MIKE HYDRO RIVER) to study the riverine flood problem of the lower Damodar river. This study used high resolution satellite data for this riverine flood affected area. The purpose of the study to identify the weak levee location along the river which is susceptible to the flood. One-dimensional hydrodynamic model was prepared for flood of 20-year return period in the lower Damodar river. High resolution RS data were used for input geometry data in the model. For simulation of the model daily discharge data used as input in the model. Model output data (water depth) match closed to observed water depth at three gauge station for the Manning's n value of 0.03. Furthermore, NSE, PBIAS, and RSR were used for determining the model performance which shows good agreement between the model output and the observed data at the gauging stations. Output of model indicates that water overtopping from river bank of lower Damodar river mostly occurred in the downstream area which is more susceptible to flooding.

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